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Nocturnal Radiation Loss Estimates for a Forest Canopy

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Average nocturnal net radiation over a conifer canopy measured with a suspended radiometer was compared with that estimated from the black body emission at the average air temperature below the radiometer, and the sky radiation measured at some distance away. Values agreed within 20 percent for 5 nights; measured radiation averaged 9 percent higher than the estimate. No systematic variation was found with windspeed or humidity.

Most radiometers are expensive and relatively fragile instruments. Their performance may be critically affected by such common hazards as precipitation and dust. These hazards are particularly severe for the unventilated instruments which, for lack of convenient power sources, must of necessity be used in most field studies. Maintenance difficulties are compounded when the instruments must be installed in a relatively inaccessible position such as above a forest canopy. A reasonable method of approximating the net radiation balance without installing and maintaining such an instrument would be preferable for most purposes.

The most convenient parameters on which to base such an estimate are the local air temperature, and the sky radiation measured nearby with more easily maintained equipment. The latter measurements can be routinely made with little difficulty. Average downward radiation from the night sky for intervals greater than half an hour should vary little between stations at the same elevation over areas of the order of 10 km^2 under most conditions of cloud cover and atmospheric moisture.

This Note briefly describes the problems encountered in such an approximation and compares resulting estimates of net radiation with measured values for data taken on 5 autumn nights in the Colorado Rockies.

The Approximation

The nocturnal radiation balance at the top of a forest stand may be expressed as

$$R_N = R_B - R_{sk} \qquad [1]$$

where R_N is the net radiation loss, R_{sk} is the downward flux of radiation from the sky, and R_B is the total thermal emission from the canopy and the soil surface. There may be appreciable temperature differences between various levels in the forest canopy and between the soil surface and the canopy, but in the absence of information on the distribution of radiating surface with height, a practical approach is to regard the canopy and soil surface as equivalent to an isothermal layer radiating at the average temperature of the actual canopy; that is, $\overline{T}$ so that

$$R_B = \sigma \overline{T}^4 \qquad [2]$$

where σ is the Stephan-Boltzman constant, and where the emissivity of the canopy elements and soil surface is assumed to be unity. In most situ-

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ations, however, foliage surface temperatures are not measured. Such temperatures for a particular foliage element could be measured with little difficulty, but the sampling problems to obtain an average temperature are formidable. In this approximation, it will be assumed that $\bar{T}$ is equal to the average air temperature in the canopy layer measured at some point between the trees. Because the actual foliage temperatures must be less than the air temperatures at any particular level in the canopy, this assumption should lead to an overestimate of R_B and thus of R_N. The differences would amount to about 7×10^{-3} ly min^{-1} for each degree of the difference between average foliage and air temperature at temperatures near 5° C. A wide range of foliage-air temperature differences are reported in the literature for leaves of various species and with differing radiation conditions and ventilation. For conifer needles, the temperature drop needed to sustain a high radiation load is of the order of one or two degrees,[2] and observed nighttime differences as measured by Wellington[3] are less than a degree. Since the needles supply the bulk of the radiating surface in a conifer canopy, the error in R_B due to foliage-air temperature differences should not exceed about 14×10^{-3} ly min^{-1}, and errors of this magnitude could be expected only with high net radiation losses.

Errors due to the temperature drop from the soil surface to the air at the lowest level of measurement are not as readily estimated. They will depend on the local windspeed, roughness, and the thermal properties of the surface as well as the total canopy cover viewed from the stand floor. Because temperature gradients of as much as 4° C. over a meter are not implausible, judging from the literature, this effect would seem to be a potential source of major error. The error in the calculated emitted radiation due to differences between the air temperature and that of the soil surface or foliage surfaces would decrease with increasing windspeed.

In general, the radiometer used to measure R_{sk} and the point at which R_N is to be estimated will not be at the same level. In most cases, the radiometer will be at a lower level, while the estimate will be for a point on some nearby slope. If these two levels are written as Z_1 and Z_2, respectively, the measured value of R_{sk} will exceed that applicable to the level Z_2 by the downward flux of radiation emitted by the air and water vapor between the levels Z_1 and Z_2. Since this emission is a function of the temperature and specific humidity of this layer, it could be computed in a routine manner—given a profile of these quantities with height—from a number of published tables or from nomograms such as the Elsasser diagram.[4] Such profiles are not generally available in most field studies, but upper bounds for such emission can be estimated from surface observations, such as a hygrothermograph recording, by assuming that neither temperature nor humidity changes through the layer. Emissions computed in this manner from temperatures and relative humidities in climatological tables vary from 10^{-3} to 10^{-1} ly min^{-1} for a layer of air 50 meters thick. It is apparent from such calculations that serious error will result in Z_1 and Z_2 differ by more than a few meters in the coastal regions of the United States, but that Z_2 may exceed Z_1 by many tens of meters in the Rocky Mountain region without appreciable error. This will be shown to be the case for the following observations.

Observations

Net nocturnal radiation loss was measured at a point in the upper reaches of a conifer canopy on a slope in the fall of 1964 at Fraser Experimental Forest. The experimental layout is shown in figure 1. These measurements were made with an unventilated Soumi-type radiometer equipped with the remote-reading and integrating thermistor circuit developed by Goodell.[5] This instrument was suspended at point A (fig. 1) by cable at a height of about 10 meters above the floor of the stand. The maximum tree height on the slope was about 20 meters, and the average height was 5 meters. All the vegetation within a radius of about 10 meters was below the instrument. Vegetation con-

[2] *Gates, D. M. Leaf temperature and energy exchange. Arch. Met. Geophys. u. Biokl. B. 12: 321-336. 1963.*

[3] *Wellington, W. G. Effects of radiation on the temperature of insect habitats. Sci. Agr. 30: 209-234. 1950.*

[4] *Johnson, J. S. Physical meteorology. 393 pp. New York: John Wiley & Sons. 1954.*

[5] *Goodell, B. C. An inexpensive totalizer of solar and thermal radiation. J. Geophys. Res. 67(4): 1383-1387, illus. 1962.*

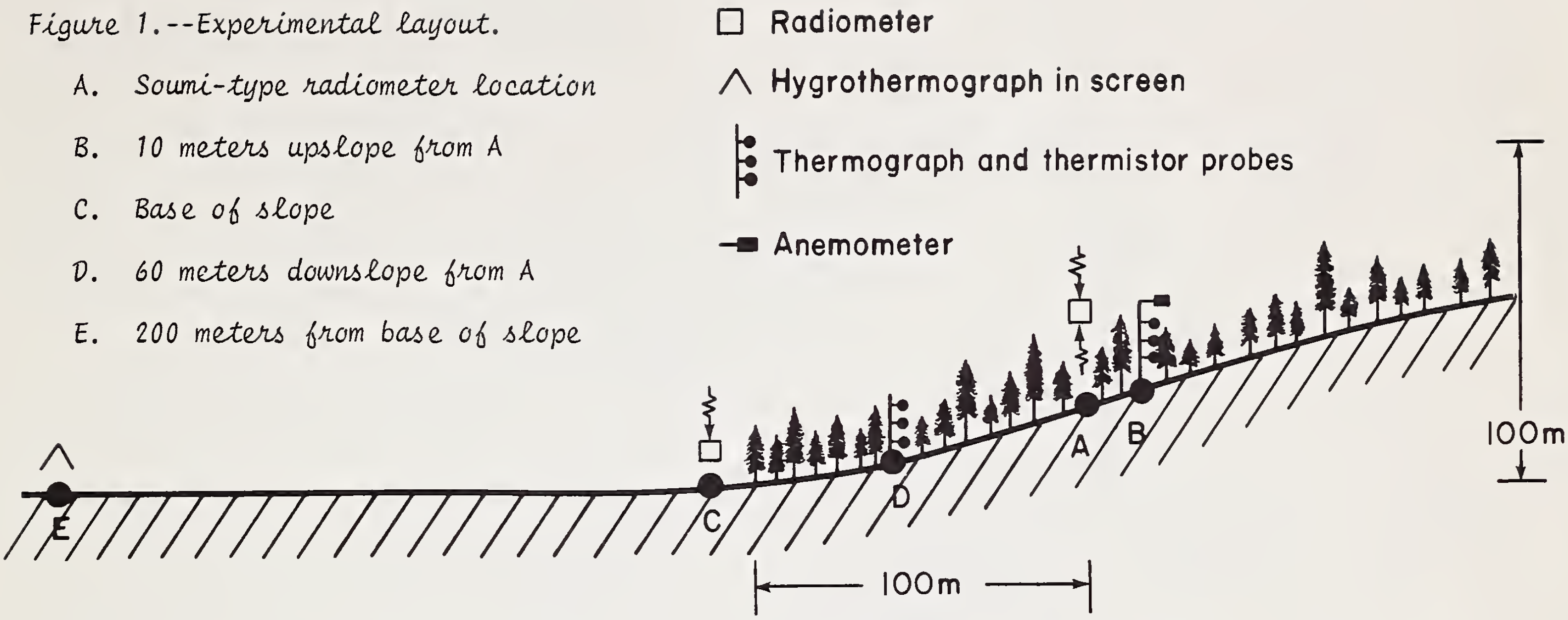

Figure 1.--Experimental layout.

A. Soumi-type radiometer location

B. 10 meters upslope from A

C. Base of slope

D. 60 meters downslope from A

E. 200 meters from base of slope

sisted of lodgepole pine, spruce, and some aspen trees.

Air temperature was measured at various levels 10 meters upslope (point B) from the instrument position and at a point (D) about 60 meters downslope. These measurements were made with remote-reading thermistors and bimetal thermographs. Windspeeds at point (B) were measured with a recording heated thermopile anemometer on a 1-meter-long cross arm attached to a tree at a level 16 meters above the slope surface.

Sky radiation was measured at (C) near the margin of the stand at the base of the slope, with a ventilated radiometer, mounted at 1-meter height, and shielded to respond to hemispherical radiation. Relative humidity and temperature data were available from a hygrothermograph maintained in a standard instrument shelter about 200 meters from the base of the slope (E).

The ventilated radiometer was at a level approximately 20 meters below the position of the radiometer on the hillside. The period of measurement was from 1800 LST, at which time the radiometer sites were in shadow, to 0500 LST the following morning, corresponding approximately to local sunrise.

Errors Due to Exposure

The use of measurements at (C) to compute the net radiation balance at the hillside radiometer station presumes either that the trees extending above the level of the slope radiometer and in the field of view of the radiometer at the base of the slope did not provide an appreciable contribution to the back radiation balance in a similar manner at the two sites. Since no measurement of canopy cover was made at the position and level of the slope radiometer, only an order of magnitude estimate may be made for this error.

Measurements with a chain and hypsometer showed that the average height of those trees within a 20-meter radius of a point directly below the suspended radiometer which rose above the level of the radiometer was about 20 meters. These trees were spaced on the average more than 5 meters apart. If we regard the screening effect of these trees on the view factor between the radiometer and the night sky as being analogous to that which would occur for a radiometer at the surface of the slope and surrounded by a dense stand 10 meters high, then by the calculations presented in Geiger's work,[6] about 50 percent of the instrument's field of view for the night sky would be obscured. However, these calculations are for a stand so dense that it may be considered opaque; that is, a solid wall. The average crown diameter of the trees above the radiometer level was only about a meter, as estimated from the ground. Such a tree at a distance of 10 meters from the radiometer would only subtend about 0.1 radians of arc.

If we approximate the radiometer position as the center of concentric polygons formed by trees 10 meters in height, spaced 5 meters apart, with an

[6]*Geiger, R. The climate near the ground. 494 pp. Cambridge, Mass.: Harvard University Press. 1957.*

effective crown diameter of 1 meter, the 12 trees of the innermost polygon subtend a total of only 1.14 radians of arc from the radiometer. The reduction in the view factor between radiometer and sky would be only 0.18 of that caused by a solid wall of the same height, and would be 0.10. The corresponding contribution for the second polygon, computed in the same way, is less than 0.02. On the basis of this very approximate model, and neglecting the variation of temperature with height in the canopy, it would appear that the radiation loss measured by the suspended radiometer could be less than that which would be measured above all the trees on the slope by about 15 percent.

The view of the radiometer at the base of the slope is also obstructed by the margin of the stand. If we consider this margin as one boundary of a clearing, Geiger's calculations imply that sky radiation measured by the radiometer may be as much as 15 percent less than would be the case if no vegetation impeded the field of view.

It should be noted that the two errors mentioned will operate in the opposite sense in respect to the comparisons made in this paper. Thus, the suspended radiometer may indicate net radiation values low by 12 percent, and the analogous error in the measured sky radiation could cause an overestimate of the net radiation computed as the difference between the sky radiation (R_{sk}) and the black body emission (R_B).

Results

The average net radiation measured at (A) is shown in table 1 as R_o for each of the 5 nights. The average air temperature ($\bar{T}$) was estimated by interpolation between points (C) and (D) and the associated thermal emission (R_B) calculated from relation [2]. The average sky radiation R_{sk} computed from the radiometer readings, and R_N computed by relation [1] is also listed for each night. The R_N and R_o sequences are remarkably close, considering the simple model on which the approximation is based: The maximum relative error is 25 percent and average relative error is 9 percent, with R_o exceeding R_N both in the average and on each night except on September 16. The sign of the divergence is surprising, since most of the error factors would cause R_N to exceed R_o.

The average windspeeds measured at (C) are low for all the nights, ranging from 30 to 52 cm sec^{-1} (table 1). The relative error in R_N does not show the expected tendency to become more negative with increasing windspeed (in fact, the maximum positive error appears at the lowest speed, on the night of September 10), nor does the relative error appear to vary consistently with the specific humidity computed from measurements at point (E).

The sign of the divergence suggests that the upper canopy is dense enough below the radiometer position at (A) to allow the foliage in the region about 3 or 4 meters below the radiometer to dominate the radiation exchange with the night sky. Thus, the temperature ($\bar{T}$) was too low by a degree or so to be representative of the radiation exchange above the canopy at (C) noted above; a correction for this effect would require information about the distribution of radiating surface within a canopy, which is not easily obtained in situations where this method would be used. On the whole, however, the estimate agrees well with the measured values, and the method can be recommended for practical problems in environments similar to the experimental site as long as limits on elevation differences are imposed by the prevailing air temperature and relative humidity are considered.

Table 1.--Estimated and measured radiation losses, 1800-0500 LST, September 1964

Date measured	Average air temperature ($\bar{T}$)	Midslope black body (R_B)	Sky (R_{sk})	Estimated (R_N)	Measured (R_o)	$\frac{R_o - R_N}{R_o}$	Windspeed	Specific humidity
	°C.	- - - - - Langleys min^{-1} - - - - -				Percent	Cm sec^{-1}	Gm. cm^{-3} x 10^6
September 10	2.9	0.473	0.453	0.020	0.025	20	30	1.8
14	1.9	.477	.460	.017	.018	5	40	2.0
16	.3	.458	.431	.027	.025	-8	46	1.7
17	.6	.457	.430	.027	.030	10	44	1.7
25	6.8	.501	.470	.031	.035	11	52	3.2